

## Saltwater Intrusion in Everglades National Park, Florida Measured by Airborne Electromagnetic Surveys

David V. Fitterman<sup>1</sup> and Maryla Deszcz-Pan<sup>1</sup>

<sup>1</sup>U.S. Geological Survey, Denver, U.S.A

### ABSTRACT

Saltwater intrusion is an ideal target for mapping with airborne electromagnetic techniques because of the high electrical conductivity of saline water and its contrast with that of freshwater. Using electromagnetic sensors to measure the electromagnetic response of the ground at several frequencies, information from various depths is obtained. The electromagnetic response is then converted to resistivity-depth models by a nonlinear parameter estimation technique called inversion.

To rapidly cover large areas of the Florida Everglades where ground access is often very difficult, the electromagnetic sensors are suspended below a helicopter which is flown back and forth across the survey area. A measurement is made every 10 to 15 m along flight lines that are typically spaced 400 m apart. The high sampling density provides a detailed picture of aquifer resistivity that is not readily obtainable by any other means. The extent of saltwater intrusion can be estimated from interpreted resistivity models.

In addition to airborne electromagnetic measurements, borehole geophysical measurements provide information on the aquifer formation resistivity and pore water specific conductance (SC). The relationship between these two properties offers a means of indirectly estimating pore-water SC from the airborne geophysical estimate of formation resistivity. Specific conductance can then be converted to chloride concentration using an established relationship for the aquifer. The resulting product is a three-dimensional estimate of aquifer water quality.

Surveys of Everglades National Park in south Florida have been made over an area of about 1000 sq. km. These maps show in detail the extent of saltwater intrusion and the influence of natural processes and human activities. The data are being used to develop ground-water flow models which incorporate salinity. The resulting flow models will be used to plan for restoration of the South Florida Ecosystem.

One advantage of the airborne electromagnetic resistivity mapping technique is the speed with which it can survey large areas where ground access is difficult or impossible. The technique works very well in the Everglades because of the sub-horizontal, slowly varying geology and absence of clay. However, it should be of use in many coastal aquifers, even where the geology is more complicated, because of the tendency of saltwater intrusion to overprint geologic boundaries and to predominate the electromagnetic response.

### INTRODUCTION

One of the principal characteristics of seawater is its high concentration of dissolved ions—approximately 35,000 mg/l [Freeze and Cherry, 1979]. These dissolved ions enhance the ability of seawater to conduct electricity. Seawater, which is a very good conductor, has a specific conductance (SC) of 50 mS/cm [Hem, 1970]. Freshwater suitable for domestic purposes

has much lower dissolved ion concentrations (0 to 1000 mg/l) and lower SC in the range of 50 to 500  $\mu\text{S}/\text{cm}$  [Hem, 1970; Freeze and Cherry, 1979; Hearst et al., 2000]. This large difference in the electrical properties of fresh and saline water means that the presence of saline water in an aquifer can be detected by various electromagnetic geophysical measurements either in boreholes, on the surface, or in the air.

In this paper we discuss how helicopter electromagnetic (HEM) measurements can be used to measure the electrical resistivity of aquifers to produce a three-dimensional view of the subsurface. Using correlations between water quality, as measured by SC and chloride content, and formation resistivity measured in boreholes, we produce a three-dimensional model of estimated water quality. Such information is of great use in developing a ground-water model which incorporates solute transport.

As an example of the HEM method we show the results of a survey flown over Everglades National Park in south Florida (Fig. 1). This survey, which is part of a larger study of the South Florida Ecosystem being conducted by Department of the Interior agencies, is aimed at understanding the impact on the ecosystem of development over the past 100 years and establishing the best course of action for restoring the system to a revitalized state [Gerould and Higer, 1999].

## **EVERGLADES HYDROLOGY**

The Florida Everglades is unique in many ways, not the least of which is the ubiquitous presence of surface water ranging from 10 cm to 2 m in depth. Surface water, coupled with sawgrass marshes and mangrove swamps, makes ground access difficult. Consequently, the traditional method of obtaining subsurface hydrologic information from boreholes and ground-water sampling is limited to existing roads or the use of portable drill rigs at remote locations. Previous hydrologic work in Everglades National Park by Fish and Stewart [1991] was based upon a dozen wells covering an area of about 2000  $\text{km}^2$ . Their work provides a very useful regional framework which defines the major hydrologic units. The hydrogeology is characterized by three distinct zones, which, from the surface to depth, are the surficial aquifer system, the intermediate confining unit, and the Floridan aquifer system. The surficial aquifer system is composed, from top to bottom, of the Biscayne aquifer, a semiconfining unit, the gray limestone aquifer, and the lower clastic unit of the Tamiami Formation. The intermediate confining unit consists of a 167- to 243-m thick sequence of green clay, silt, limestone, and fine sand [Parker et al., 1955, p. 189]. These sediments have relatively low permeability and produce little water. The Floridan aquifer system is not of importance to our work because of its great depth (290 to 305 m) in Miami-Dade County [Miller, 1986].

In terms of ground-water supply, the most important unit is the Biscayne aquifer. The Biscayne aquifer contains high permeability limestone and calcareous sand units. Fish and Stewart [1991] require that there be at least a 3-m section of greater than 305 m/d horizontal permeability for these units to be considered part of the aquifer. The base of the Biscayne aquifer is defined as the depth where the subjacent sands and clayey sands fail to meet this permeability criterion. In the study area the Biscayne aquifer ranges from 0 to 30 m thick; its thickness increases toward the east.

Below the Biscayne, a second aquifer composed of a gray limestone unit of the Tamiami Formation is found at depths of 21 to 49 m in western Miami-Dade County [Fish, 1988; Fish and Stewart, 1991]. While less permeable than the Biscayne aquifer, the gray limestone aquifer is

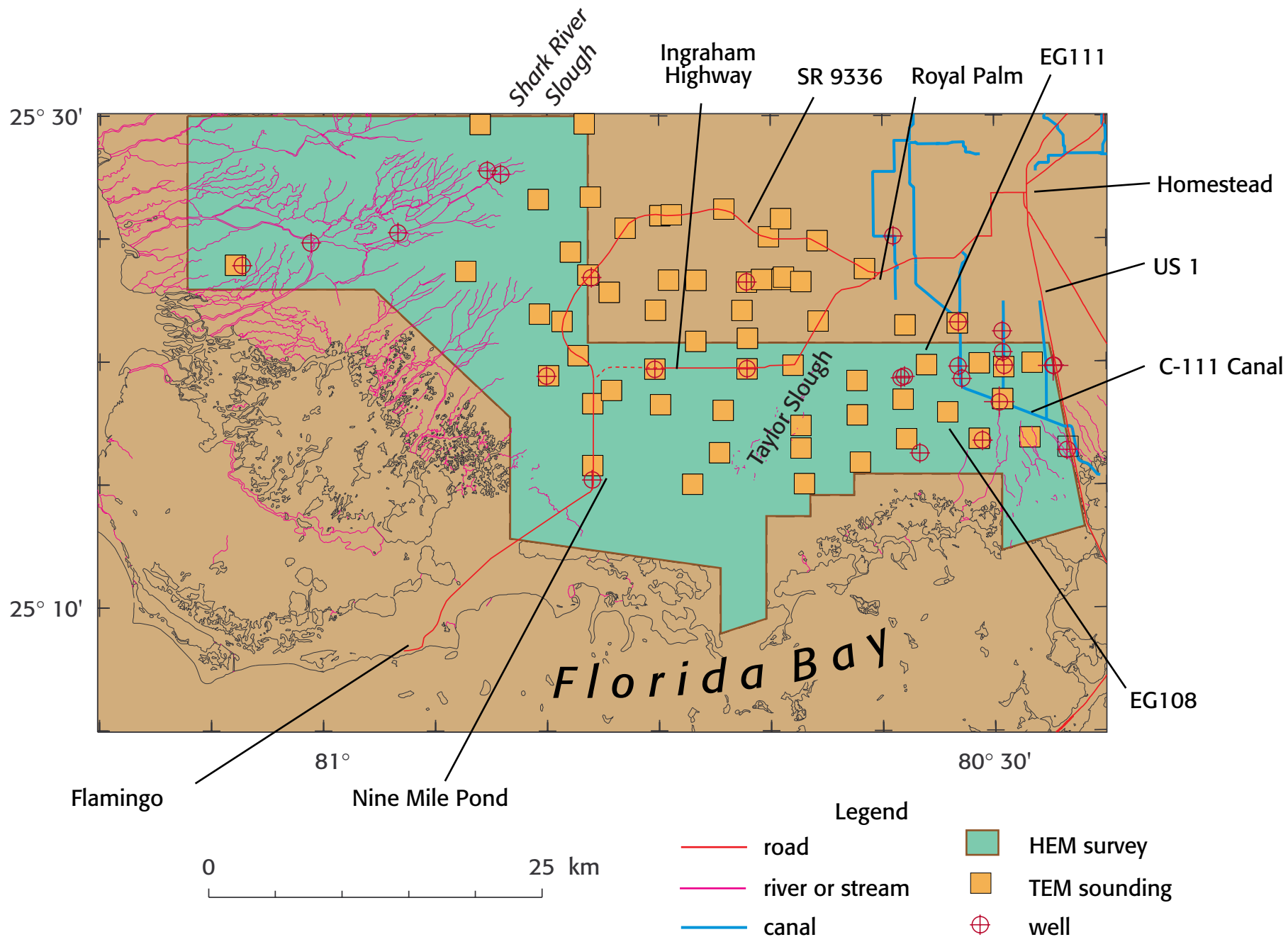


Figure 1 Location map showing the HEM survey, TEM soundings, and observations wells used in this study. The maps includes portions of Everglades National Park and surrounding areas.

still significant, especially in the western portion of the study area where the Biscayne aquifer does not exist.

## ELECTRICAL RESISTIVITY OF GEOLOGIC MATERIALS

Most geological materials are composed of minerals which are electrical insulators at the temperatures usually encountered in the near-surface environment. Typically, rocks can conduct electricity only through fluid filled pores and fractures. Early work on Gulf coast sedimentary rocks by Archie [1942] found that the electrical resistivity of a formation is proportional to the electrical resistivity of the saturating pore fluid and inversely proportional to the porosity raised to a power. More exactly he developed the following relationship

$$F = \rho_f / \rho_o = a \phi^{-m}$$

where  $F$  the formation factor,  $\rho_f$  is the formation resistivity,  $\rho_o$  is the pore fluid resistivity,  $\phi$  is the porosity, and  $a$  and  $m$  are constants specific to a formation. In general,  $a$  is approximately constant and equal to 1, whereas  $m$  varies with lithology: 1.3-1.45 for unconsolidated sand, 1.39-1.58 for marine sands, and 1.8-2.0 for sandstones. This expression is valid for sedimentary rocks when there is little or no clay in the pore spaces and the pore fluid has moderately low electrical resistivity, or when the rocks are saturated with very low resistivity fluid such as seawater. For a sand or sedimentary rock aquifer with a porosity of 30 percent and a pore fluid resistivity of 0.25 ohm-m typical of seawater, the formation resistivity would be in the range of 1.2 to 3.3 ohm-m. Fluid resistivity is related to SC through the formula

$$\rho_f [\text{ohm-m}] = 10000 / SC [\mu\text{S/cm}].$$

Saturating the same aquifer with freshwater ( $\rho_o$  of 20 to 200 ohm-m) would result in a formation resistivity of 100 to 2000 ohm-m. Thus we predict one to two orders of magnitude difference in electrical resistivity between a freshwater and saltwater saturated aquifer. This large contrast makes an excellent target for electromagnetic geophysical techniques.

There are several factors which can influence the resistivity predicted by Archie's law. First, the presence of clay minerals in the pore space reduces the formation resistivity predicted by Archie's law [Waxman and Smits, 1968]. In this case to predict the formation resistivity it is necessary to know both the cation exchange capacity of the clay and the amount of clay present. In general, the electrical resistivity would be lowered for a freshwater saturated aquifer by a factor of 1.5 or more depending upon the amount and type of clay, while the resistivity of a saltwater saturated aquifer would be lowered very slightly. Second, the presence of fractures in an aquifer also lowers the predicted formation resistivity.

## HELICOPTER ELECTROMAGNETIC SYSTEM

The helicopter electromagnetic (HEM) resistivity mapping was an outgrowth of HEM methods developed for mineral exploration [Fraser, 1978; Palacky 1986; Fitterman, 1990]. The methods use a transmitter coil, which is continuously driven by a sinusoidally varying current, and a receiver coil to measure the inphase and quadrature electromagnetic response. The coils are mounted in a cigar shaped enclosure called a bird which is about 10 m long. The bird is slung about 30 m below a helicopter. The helicopter flies back and forth over the survey area with the bird at an altitude of about 30 m above the ground (see Fig. 2). The electromagnetic response is measured every 0.2 s resulting in a spatial sampling of about 10-15 m along flight lines.

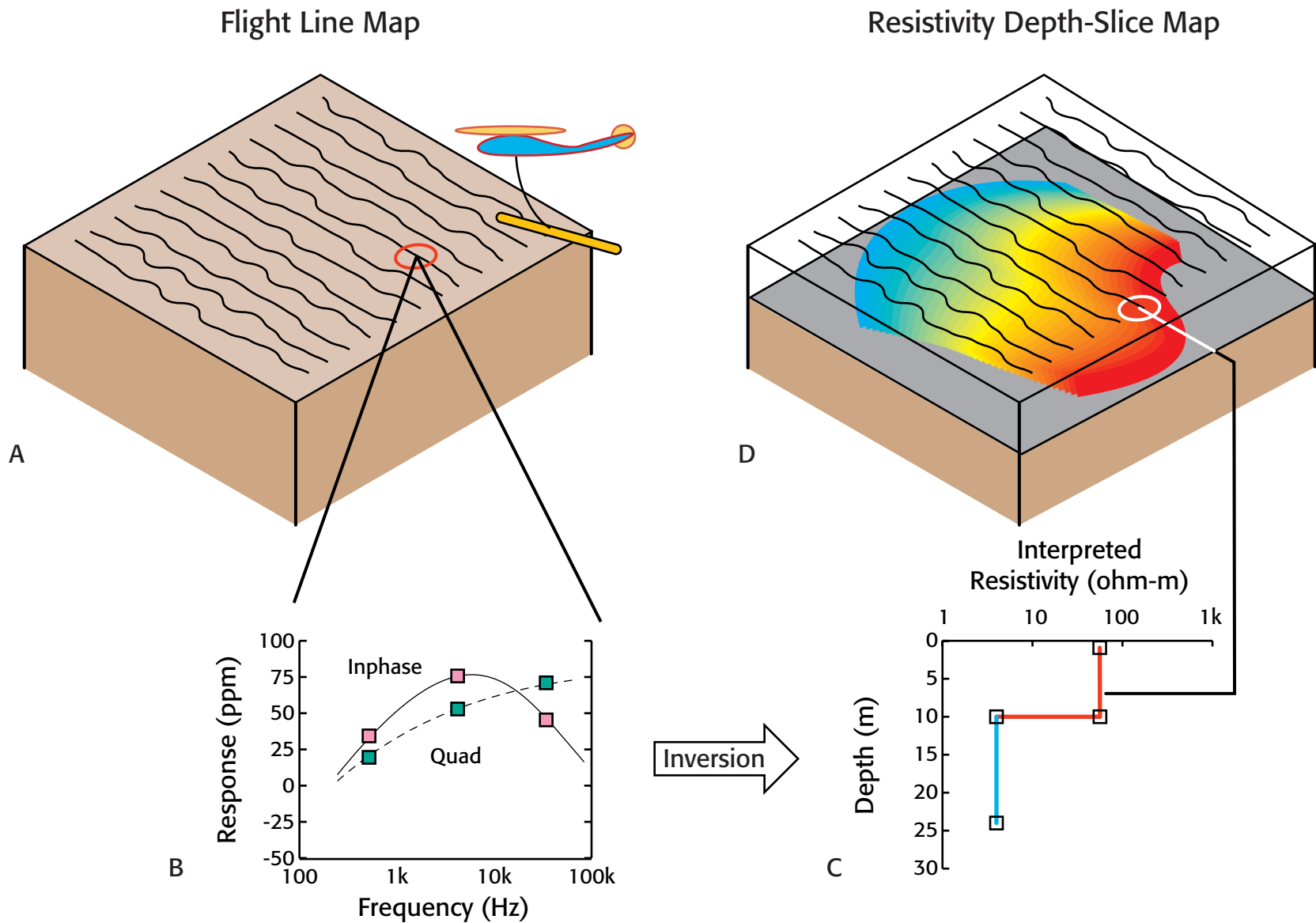


Figure 2 Schematic representation of HEM data collection and interpretation. A) Flight lines are flown along parallel lines spaced 400 m apart. B) The bird measures the inphase and quadrature electromagnetic response at several frequencies. C) The measured response is used to determine the resistivity-depth function by a process called inversion. D) The resistivity-depth functions are combined to produce an interpreted resistivity depth-slice map.

The bird contains several coil pairs operating at different frequencies in the range of 900-56,000 Hz. Lower frequencies sense deeper into the ground. The data are inverted to obtain a layered earth model at each measurement point, and the results are then converted into resistivity-depth-slice maps [Fitterman and Deszcz-Pan, 1998]. In conductive regions such as a shallow saltwater intruded zone with a resistivity of less than 10 ohm-m, the depth of exploration is about 15 m, while for freshwater saturated locations with higher resistivities (30-100 ohm-m) the depth of exploration can exceed 60 m.

## **ESTIMATION OF AQUIFER WATER QUALITY**

While 3-D geophysical models of subsurface resistivity are very informative and provide information on spatial resistivity variations that can not be readily obtained by any other means, they are less valuable to hydrologists than 3-D models of hydrologic parameters estimated from the geophysical data. Making this critical transformation is often difficult and sometimes impossible. We have endeavored to take this step by estimating formation factor  $F$ . Knowing the formation factor, the formation resistivities obtained from the airborne geophysical measurements can be used to estimate the SC of the pore fluid. If, in addition, the relationship between specific conductance and chloride concentration is known, then the chloride concentration of the formation can be estimated from the geophysical data. Laboratory measurements of water samples provide a means of determining this latter relationship.

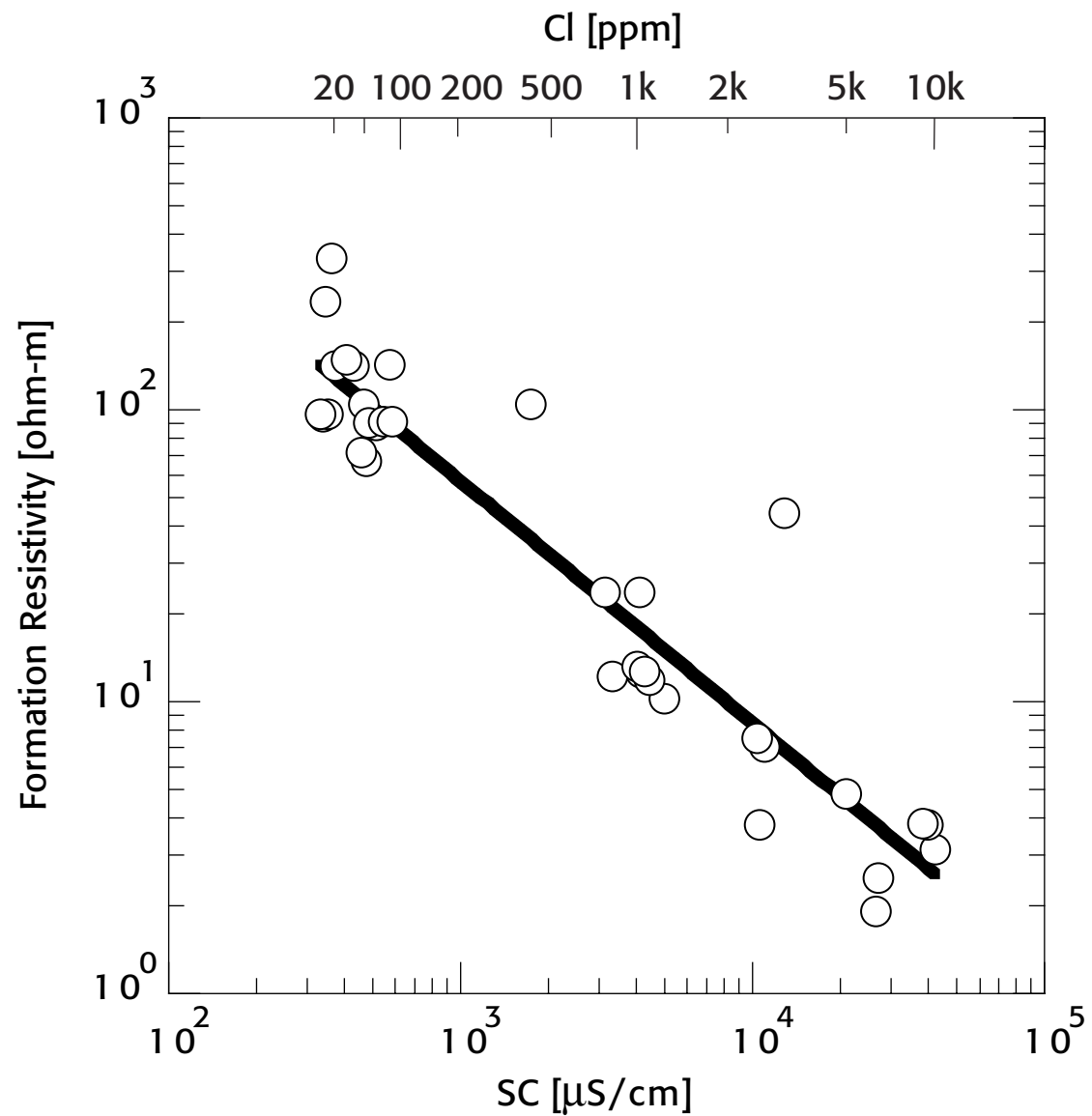
To estimate the formation factor, induction logs were measured in a total of 23 boreholes (Fig. 1). This provided very detailed resistivity-depth information. The formation resistivity was averaged over the screened interval of the wells (typically 3 m). The wells were then pumped and a water sample collected after sufficient time for the well bore to be purged. The SC of the sample was measured. For shallow wells the conductivity was directly measured in the well.

The data for all of the measured wells is shown in Fig. 3. Both the formation resistivity and SC span over two decades giving a good range of values for developing a correlation. Due to the inherent scatter in the data, the pore-water conductivity is estimated from the formation resistivity with an uncertainty of a factor of 2-3. Some of this uncertainty stems from the fact that the wells are from a wide range of depths with some of the deeper wells being below the Biscayne aquifer. Thus there are some differences in the geologic units, though all wells were screened in porous zones which were good water producers. While this uncertainty is much larger than expected for conductivity probe or laboratory measured values, it is adequate for use in regional scale aquifer studies where the value of SC would be interpolated between wells that are 10 or more kilometers apart.

Also shown on the graph is a scale corresponding to the estimated chloride concentration. This scale is based on an empirical relationship between SC and chloride concentration which is valid for surface and near-surface waters in Dade County [A. C. Lietz, USGS Miami, written commun., 1998].

## **EVERGLADES NATIONAL PARK HEM SURVEY**

We present the results of an HEM survey flown over portions of Everglades National Park and surrounding lands (see Fig. 1). The survey, which covers about 1036 km<sup>2</sup> at a line spacing of 400 m, took five days to fly. The data were interpreted using layered earth models as outlined above, and depth-slice maps were created. Four depth slices are shown in Fig. 4. These particular maps were chosen because there are significant changes between them. In all four depth-slice maps there is a general decrease in resistivity toward Florida Bay in the south as a result of



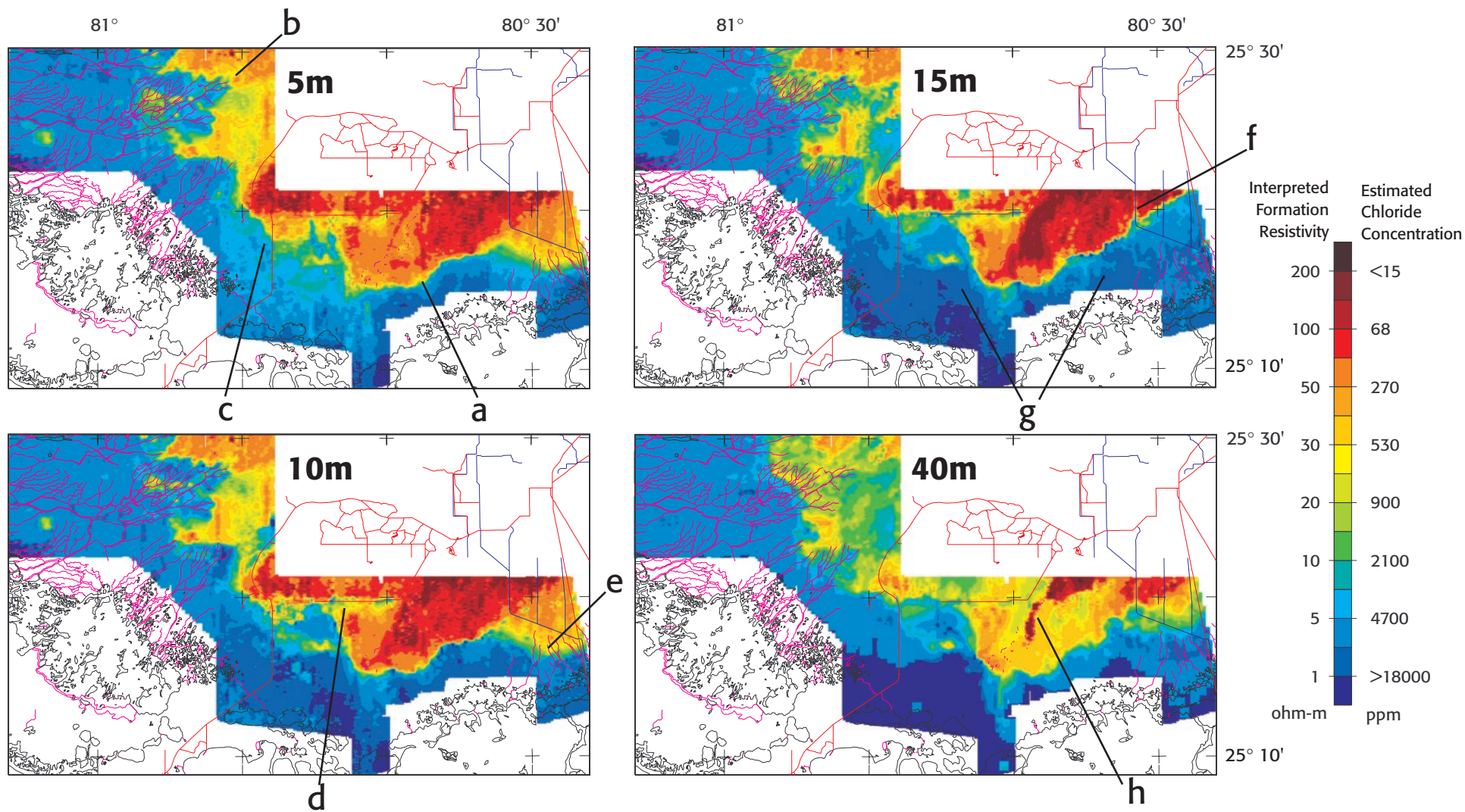


Figure 4 Interpreted HEM resistivity-depth-slice map from Everglades National Park for depths of 5 m, 10 m, 15 m, and 40 m. Annotated features are discussed in the text.

saltwater intrusion. The freshwater/saltwater interface (FWSWI) occurs between a resistivity of 10 to 30 ohm-m (Fitterman et al., 1999). The freshwater saturated zone has resistivities of greater than 30 ohm-m, and the saltwater saturated zone has resistivities of less than 10 ohm-m. Throughout the Taylor Slough area (feature a) the FWSWI occurs over a short distance. The trace of the transition varies smoothly because the hydrologic conditions are practically uniform. The position and shape of the FWSWI is controlled by the balance between ground-water flow to the south, evapotranspiration losses, and saltwater intrusion. To the west (feature b), tidal rivers drain the area and allow seawater to move inland a great distance. The result is a less abrupt transition from freshwater to saltwater saturated zones; the transition is spread over a greater distance than it is near Taylor Slough. Parallel to the interface, there is more variability in the landward extent of saltwater intrusion because of the numerous rivers, which lower the hydraulic head.

The resistivity depth slices show that several man-made structures have a significant influence on the hydrology. Along the main park road (feature c) there is a four-fold change in resistivity from one side to the other. This feature, which extends to at least 10-m depth, is due to the roadbed blocking the westward flow of freshwater from Taylor Slough. Roads play an important role in controlling the flow of surface water because they are typically raised 1-2 m above the water covered marshes. Along old Ingraham Highway (feature d) a conductive zone is seen. This road was constructed between 1915 and 1919 by digging a canal and piling up the dredged material to form the roadway. The resulting canal was originally open from Florida Bay near the town of Flamingo all the way to Royal Palm (Fig. 1). Seawater migrated inland along this entire section of the canal. The canal was plugged in 1951. We believe that this low resistivity anomaly is due to seawater which remains in the aquifer.

The C-111 canal (Fig. 1) is a major canal which drains into Biscayne Bay. One of its current functions is to provide water to the southeastern portion of Everglades National Park. This is accomplished through breaches in the southern bank of the canal from the bend in the canal to highway U.S. 1. (The southern bank of the canal was completely removed by early 1998.) In the 5-m and 10-m depth slices a resistivity high (feature e) is seen to the south of the canal because of freshwater recharge from the canal. This recharge produces a freshwater zone to the south of the main FWSWI location seen in the 10-m and 15-m depth slices. In the 15-m depth slice a cusp in the FWSWI (feature f) is seen where the C-111 canal crosses the interface. This cusp is produced by water impoundment behind a moveable dam on the canal (control structure S18C).

One issue of concern to studies of Florida Bay is whether fresh ground-water flows to Florida Bay. The HEM results indicate that no freshwater zone exists south of the FWSWI (feature g). Thus it is highly unlikely that fresh, ground-water flows to Florida Bay. In all of the depth slices a high resistivity zone associated with Taylor Slough (feature h) is seen. Taylor Slough is the major source of water to the central portion of Everglades National Park. From the HEM interpretation this zone extends to a depth of at least 40 m. This feature may be caused by fresh, surface water recharging the aquifer under the slough. The slough is probably an erosional feature that formed during periods of lower sea level, and then filled with sediments as sea level rose.

## CONCLUSIONS

The HEM method provides a way of mapping subsurface resistivity which can be correlated with aquifer water quality. Unlike conventional hydrologic methods based solely on

drilling and sampling, the HEM method is feasible in areas where ground access is difficult. Because of the high spatial sampling density of the method, the resulting maps show much more detail than could be obtained from sampling wells alone. Many features related to saltwater intrusion and the impact of roads and canals on water flows can be seen in them. A correlation between formation resistivity and water quality was established using borehole measurements. This correlation allows the resistivity models to be interpreted as estimated water quality. This type of information is very valuable when trying to develop solute transport models for the ground-water system.

The success of the HEM method in Everglades National Park can be attributed to the relatively horizontal nature of the geology which changes gradually from place to place. In more geologically complex regions with sharply folded beds and faults, the use of layered-earth models to interpret HEM data would be less reliable or not feasible. The absence of significant amounts of clay in the Biscayne aquifer also contributes to the success of the method. Thick and extensive clay units have low resistivity values that might be confused with saltwater intrusion. In areas with such clays, reliable interpretation of saltwater intrusion is likely to be difficult.

The use of the HEM method for hydrologic problems has a great deal of promise because of the method's ability to quickly obtain a three-dimensional view of an aquifer and water quality. Based on the success of this and other studies [Sengpiel, 1983; Sengpiel, 1990; Sengpiel and Siemon, 1998; Wynn and Gettings, 1998] we expect to see increased use of the method for hydrologic studies.

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**Corresponding author:** David V. Fitterman, U.S. Geological Survey, Box 25046 MS 964, Denver, CO, USA. Email: [fitter@usgs.gov](mailto:fitter@usgs.gov)